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## A preliminary synthesis of major scientific results during the SALSA program

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### Abstract

The objective of this paper is to provide an overview of the primary results of the Semi-Arid Land–Surface–Atmosphere (SALSA) Program in the context of improvements to our overall understanding of hydrologic, ecologic, and atmospheric processes and their interactions in a semi-arid basin. The major findings and future research needs associated with the different core components of the program are emphasized. First, remote-sensing investigations are discussed, especially those directed toward taking full advantage of the capabilities of the new generation of satellites (ERS2/ATSR2, VEGETATION, LANDSAT7, NASA-EOS). Second, we discuss parameterization of the water and energy fluxes in arid and semi-arid regions, with special emphasis on methods to aggregate these fluxes from patch scale to grid scale. Third, we address the issues related to grassland ecology and competition for water between native grass and invasive mesquite species. Fourth, findings related to the interactions between surface water, ground water, and vegetation in a semi-arid riparian system are discussed. Next, an assessment of land use and land cover change over the entire basin over a quarter century is reviewed. Finally, unsolved issues and the needs for further research are outlined. © 2000 Elsevier Science B.V. All rights reserved.

**Keywords:** SVAT modeling; Remote-sensing; Vegetation functioning; Hydrology; SALSA; Semi-arid; San Pedro river; Riparian; Ecology

### 1. Introduction

The coupling of surface processes and climate occurs at different temporal and spatial scales and is not fully understood. For example, evaporation from the land surface and the development of the atmospheric boundary layer interact at time scales of hours,

whereas changes in root zone soil moisture and synoptic weather patterns occur over time scales of days to weeks (Betts et al., 1994). Additionally, fluxes of CO<sub>2</sub> and other greenhouse gases depend on the biophysical properties of the land surface. Natural and human induced changes in land cover modify the uptake and release of these gases, leading to changes in their atmospheric concentration which may influence global atmospheric circulation (Dickinson, 1995; Sellers et al., 1996; Bonan, 1995; Avissar, 1998).

Regions classified as semi-arid or arid constitute roughly one-third of the total global land cover. Within

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these regions, the dynamic water balance is the single most critical factor in the sustainability of the ecosystems and human populations. Many landscapes in the southwest United States, northern Mexico, and elsewhere have been permanently altered by activities that have modified the water cycle, such as rapid urbanization, ground water mining, overgrazing, and fire suppression (Swetnam and Betancourt, 1998). The serious environmental and economic consequences of these activities have led to a pressing societal need for detailed scientific studies of these complex processes. First, it is important to understand how alterations to the landscape have occurred, then to improve forecasts of the probable consequences of continuing disturbances (whether natural or human-induced) on the scarce natural resources and, finally, to provide scientific tools for decision making.

In this context, a consortium of universities, research laboratories, and government agencies from the United States, Mexico, and France designed the Semi-Arid-Land-Surface-Atmosphere (SALSA) Program. The primary goal of SALSA is to understand, model, and predict the consequences of natural and human-induced changes on the basin-wide water balance and ecological diversity of semi-arid regions at event, seasonal, interannual, and decadal time scales. The program focuses on the San Pedro river basin, which originates in northern Sonora, Mexico and flows north into southeastern AZ. However, since the ecological, hydrological, and meteorological processes involved are not specific to the San Pedro river basin, the results obtained and the expertise gained during this phase of the SALSA program will also be applied to other semi-arid region of the world. In contrast to previous multidisciplinary programs in semi-arid areas such as Monsoon'90 (Kustas and Goodrich, 1994), EFEDA (Bolle et al., 1993), and Hapex-Sahel (Goutorbe et al., 1994), SALSA is a long-term (5–7 year) effort.

In order to address the primary objective of the SALSA program, an improved understanding of the hydrological, meteorological, and ecological processes and their interactions at different space-time scales is needed (Wallace, 1995). This requires a synergistic approach that cuts across disciplines and temporal and spatial scales. The needs and the problems associated with each of the program components, from both observational and modeling perspectives,

were identified and translated into secondary objectives that served to integrate the research of several disciplines (Goodrich et al., 2000a).

The objective of this paper is to provide an overview of the scientific results obtained in the course of the first three years of the SALSA program. The paper is organized such that significant accomplishments with respect to each of the secondary SALSA objectives are highlighted. In Section 2.1, we present the results associated with remote-sensing research, especially that directed toward the use of new-generation satellite data. In Section 2.2, we address the parameterization of the fluxes of water and energy in arid and semi-arid regions. The main question here is to determine the level of detail and complexity in these parameterizations that is really needed to capture the spatial and temporal variability of the surface fluxes. Similarly, we discuss the representation of heterogeneity for the surface-controlling parameters. Here again, the objective is to identify those land-surface parameters or attributes which are most important in semi-arid regions, as well as the level of complexity required in the aggregation procedures, which relate local and effective values, in order to reproduce the observed aggregate fluxes. In Section 2.3, we present results about what has been learned in terms of the vegetation functioning and dynamics in the basin with special emphasis on the competition for water between two major lowland biomes in the basin (grass and mesquite). In Section 2.4, the interaction between ground water, surface water, and riparian vegetation in a globally important semi-arid riparian area is addressed. In Section 2.5, conclusions regarding the assessment of land use and land cover changes in the San Pedro are presented. Finally, Section 3 contains a general discussion of the contributions of the SALSA program toward improving our overall knowledge of the surface processes occurring in semi-arid zones. Unsolved issues and the future research needed are also outlined.

## 2. Key results from SALSA

### 2.1. Remote-sensing investigations

Several factors have contributed to the important role of remote sensing during the SALSA program.

Satellite observations are the most plausible way of providing long-term global measurements of the state of the land surface and atmosphere (Running et al., 1995; Nemani et al., 1996). Additionally, the San Pedro river basin has been selected as a validation site for several remote-sensing programs (NASA Earth Observing System ASTER and MODIS, ERS2/ATSR2, LANDSAT 7, ATLAS, SPOT4/VEGETATION). SALSA investigations associated with remote-sensing techniques covered a wide range of topics (Moran et al., 1998). In the following paragraphs, we present the results obtained regarding the use of remotely sensed data to monitor and to infer surface and atmospheric variables; the use of remote-sensing of surface temperature for estimating surface fluxes; and finally, methods to assimilate remotely sensed data and calibrate surface process models.

#### *2.1.1. Monitoring surface characteristics and inversion of biophysical parameters from remotely sensed data*

Several studies were specifically aimed at developing direct and inverse models to link surface parameters and variables with remote-sensing observations in different wave bands. Pinker et al. (2000) utilized GOES-8 observations to derive clear sky short-wave radiative fluxes and surface albedo during the 1997 season. They reported important discrepancies between observed and retrieved fluxes and albedo when climatological values for aerosol concentrations are used. They also reported that the performance of the retrieval scheme significantly improved when observed aerosol values are used. This is of interest since maps of aerosol concentrations will be provided by new generation satellite data from EOS platforms.

Nouvellon et al. (2000b) investigated the effects of clumping, sky conditions and soil albedo on PAR extinction coefficients in short-grass ecosystems from both modeling and experimental perspectives. They reported that these effects were very significant for low cover, but much smaller in higher cover conditions. They also reported that instantaneous PAR absorption was significantly sensitive to directional effects. Because of this, the use of a constant extinction coefficient in canopy photosynthesis models working at hourly time steps results in inaccurate estimations of the PAR absorbed by the canopy.

Moran et al. (2000) used an approach that combines C-band ERS2-SAR and Landsat TM data to map surface soil moisture during the 1997 season. They used the difference between dry and wet season SAR backscatter to normalize roughness effects, and utilized surface reflectance from TM images to account for changes in vegetation density. They found that the combined SAR/TM approach greatly improved estimates of the spatial and temporal variation of surface soil moisture over semi-arid rangeland. However, they also reported that the overall sensitivity of the SAR backscatter coefficient to soil moisture is limited, and an accurate estimate of green leaf area index (GLAI) is required. In this regard, Qi et al. (2000) developed an empirical approach for using remotely sensed data from Landsat TM, SPOT 4 VEGETATION, and aircraft sensors to quantify the spatial and temporal dynamics of GLAI and of the fractional green vegetation cover ( $f_c$ ) over the San Pedro river riparian corridor and the basin. This approach is based on the concept of pseudo-invariant objects and consists of three steps. They first define areas of the scene where GLAI and  $f_c$  are invariant with time (large bare soil patches). Second, they derive the GLAI and  $f_c$  as empirical functions of vegetation index and finally they subtract the GLAI ( $f_c$ ) values of the bare soil patch from the entire images to compute GLAI ( $f_c$ ) maps. The comparison of remotely estimated  $f_c$  and GLAI with limited ground-based measurements was encouraging. However, the fact that a single empirical relationship has been used to derive GLAI from a vegetation index may not be generalized to all vegetation types that can be found in the images. This leads to a bias toward the type of vegetation for which the relation has been developed. Additionally, the case of mixed vegetation pixels is yet to be addressed.

Cayrol et al. (2000a) compared reflectance data in the red, near infrared, and short-wave infrared (SWIR) bands measured by the VEGETATION sensor on-board SPOT-4, after being corrected for atmospheric and directional effects, to observed biomass and LAI during the 1998 and 1999 seasons. The results indicated that the sensitivity of the SWIR and red bands to the amount of vegetation were rather similar. This suggests that, because the SWIR is less sensitive to atmospheric perturbations than the Red band, a combination of the 3 bands may be more effective in

characterizing vegetation status and dynamics than the usual two band approach.

### 2.1.2. Remotely sensed surface temperature

The use of remotely sensed surface temperature for estimating surface fluxes has been heavily investigated. In contrast to the finding of Hall et al. (1992), it has been shown here that radiative surface temperature can be used successfully to estimate instantaneous values of sensible heat flux, if the difference between radiative and aerodynamic surface temperature is taken into account. In this regard, it has been pointed out that the approach of adding an excess resistance to the aerodynamic resistance in the formulation of the sensible heat flux is functionally equivalent to the  $\beta$  approach of Chehbouni et al. (1997b), which consists of modifying directly the temperature difference. Both need to be calibrated locally. It should be mentioned however, that the excess resistance should not be confused with the  $B^{-1}$  factor, as it is often done in the literature. The  $B^{-1}$  factor is not meant to take into account the difference between radiative and aerodynamic surface temperature, but rather the difference between roughness length for heat and for momentum. Watts et al. (2000) used AVHRR-based surface temperature in conjunction with the  $\beta$  approach to derive sensible heat flux over a grassland site in Mexico. Estimates of sensible heat flux compared very well with those from the Eddy correlation and the scintillometer. Chehbouni et al. (2000a) extended this approach to a surface composed of two adjacent patches (mesquite and grass). They concluded that it is inappropriate to use a relationship between model and observational variables (here radiative and aerodynamic surface temperature) that was developed and calibrated at patch scale for an application at a larger scale by simply scaling the parameters involved in its formulation. Therefore, future research should be directed towards building robust relationships between model and observational variables directly at the large scale.

In the framework of the ATSR investigation, the effect of view angle on radiative surface temperature has been studied. Surprisingly, directional effects on thermal infrared observations have not received as much attention as in the optical region. As for visible and near-infrared observations, the relative contribution of soil and vegetation to radiative surface temperature measurements varies with the view angle. The differ-

ence between nadir and off-nadir surface temperature therefore increases with increasing contrast between soil and the vegetation. Experimental data collected over a sparse grassland site in Mexico indicate differences between nadir ( $0^\circ$ ) and off-nadir radiative ( $45^\circ$ ) temperature of up to  $6^\circ\text{C}$ . The data also illustrated that, under constant vegetation conditions, this difference is well correlated with surface soil moisture. However, the correlation decreases when the same comparison is made under changing vegetation conditions. The correspondence between surface temperature difference and surface soil moisture is still visible, but the scatter is large. This indicates that there is also a dependence on vegetation status and type. Current research is being directed toward the quantification of this dependence on vegetation status using remotely sensed data in the visible, NIR, and SWIR bands. Additionally, the impact of pixel heterogeneity (mixed pixels) on its directional behavior in the thermal infrared region is yet to be investigated.

### 2.1.3. Assimilation of remotely sensed data in surface process models

Sensors on Earth-orbiting satellites can only provide occasional snapshots of the Earth's surface. The maximum frequency for these snapshots for a given area depends on the orbital characteristics of the satellite and the field of view of the sensor. Furthermore, the usable data are usually much reduced by the presence of clouds (except for sensors operating in the microwave region). Thus, satellite data alone are not adequate for monitoring many important surface processes, such as turbulent fluxes. One possible solution is to couple the satellite data to a process model which uses widely available information from surface meteorological stations. These models can provide continuous information about surface processes and should be able to incorporate satellite data when available. The approach used in SALSA is based on the principle of minimizing the difference between a given set of variables measured by satellite and those simulated by the process model coupled to a radiative transfer model. This is accomplished by tuning some of the unknown (constant) parameters of the surface process model. This approach has been successfully tested during SALSA and elsewhere (Moulin et al., 1995, 1998; Fischer et al., 1997; Nouvellon et al., 1998; Cayrol et al., 2000b). However, there are several conditions

that must be satisfied in order to apply this approach. First, the radiative transfer model needs to be accurate so that the satellite observations can be well reproduced. Second, directional and atmospheric effects need to be either removed from the data or reproduced by the radiative transfer model. Third, the unknown or poorly known parameters to be “tuned” should be carefully selected in the sense that they should strongly influence the remotely sensed observations. Fourth, their number should be limited, because satellite sensors only acquire a few independent variables.

Using this scheme, if we assume that we have a perfect model and error-free data, it would appear that remotely sensed data are only needed in an initial calibration phase to obtain appropriate values for the critical parameters in the model (and can be dispensed with thereafter). In the real world, however, our models are far from perfect, and the data are always imprecise so that the model results are likely to diverge from the true values. In this situation, the sequential assimilation of remote sensing based state variables may appear more effective in keeping the model on track (Houser et al., 1998; Castelli et al., 1999; Li and Islam, 1999). It should be noted, however, that the sequential assimilation approach requires that the equations of both process model and radiative transfer model be linearized. It also requires estimates of error in the data and in the model outputs which is not a trivial task, especially if the models are highly non-linear. A realistic option might be through the combination of both the above approaches. Research is currently underway for simultaneous four-dimensional assimilation of several streams of remotely sensed data, such as those from NASA-EOS platforms, into a coupled land-surface atmosphere model (Shuttleworth, 1998).

## 2.2. *Flux of water energy at different space-time scales*

### 2.2.1. *Soil vegetation atmosphere transfer (SVAT) models*

The issue of estimating the flux of water and energy in the soil–vegetation–atmosphere continuum has been heavily investigated during the SALSA program. A wide spectrum of approaches and models, ranging from very simple to more complex, has been employed over different biomes in the San Pedro river

basin. Boulet et al. (1999) used the original and a modified version of the Sispat model (Braud et al., 1995) to investigate the effect of local scale heterogeneity on surface fluxes. Sispat is a vertical one-dimensional SVAT model, where the coupled heat and mass (both liquid and vapor) transfers in several soil layers are described. The soil–plant–atmosphere interface is represented (in the original version) by a two-layer approach following Shuttleworth and Wallace (1985). The modified version uses a two-surface compartment or mosaic model (Chehbouni et al., 1997a). These two compartments are (1) the vegetation and a shaded soil layer underneath, and (2) the unshaded bare soil. These compartments are assumed to behave independently from each other (Lhomme and Chehbouni, 1999). The performances of both versions were evaluated using data taken over sparse and homogeneously distributed grass in Mexico and over sparse but heterogeneously distributed shrubs (patchy) in the US. The results showed that the relative accuracy of the two models depends on the value of the sparseness index, which is defined as the ratio of the typical length scale of the patches of bare soil between the vegetation elements, divided by the typical height of the vegetation. Thus, the mosaic representation gives a more accurate description of the energy balance when this index is large. However, when the sparseness index is low, the two-layer approach gives more accurate results. Additional work is needed to further document this issue. First, the effect of the vegetation compartment on turbulence above the bare soil needs to be taken into account in the mosaic approach. Second, the value of the sparseness index above which a mosaic representation would be required is still not well defined. Third, the potential for deriving the value of the sparseness index from multidirectional reflectance data needs to be investigated.

A second type of SVAT has been used by Cayrol et al. (2000a). This SVAT model is similar to Sispat as far as the surface scheme is concerned, but the soil component is modeled using the force restore approach. This model was evaluated using data collected over a grassland site in Mexico during the 1997 and 1998 monsoon seasons. The results showed that the model was able to reproduce the observed surface fluxes in 1997 very well (RMSE, root mean square error, of  $26 \text{ W m}^{-2}$  for latent heat flux). Finally, a third SVAT, which is based on a simple bucket represen-

tation with one bulk surface of mixed vegetation and soil and a single soil reservoir, has been developed during SALSA (Boulet et al., 2000). This model uses the concept of infiltration and exfiltration capacities to describe water infiltration and exfiltration from a bucket whose depth corresponds to the hydrologically active depth. The forcing is divided into storm and interstorm periods, and the well-known three-stage representation is used for both infiltration and exfiltration (Salvucci and Entekhabi, 1994; Salvucci, 1997). The model performance was evaluated using data acquired over a grassland site in Mexico as well as with the results from Sispat, and satisfactory agreement was obtained in both cases (RMSE of about  $35 \text{ W m}^{-2}$  for latent heat flux). Once again, it appears that complex surface schemes might not be needed to accurately describe the fluxes of water and energy in semi-arid regions. It is possible that a simple surface scheme, in which the difference between radiative and aerodynamic surface temperature is taken into account and the bulk surface resistance to water transfer is described in terms of moisture availability and some index of plant attribute or vigor, may perform as well as more complex schemes.

#### 2.2.2. *Spatially distributed/averaged estimate of surface fluxes and aggregation procedures*

The estimation of spatially distributed/averaged surface fluxes has been addressed in the course of SALSA from both measurement and modeling perspectives. A volume-imaging Raman lidar has been used in conjunction with maps of friction velocity (either measured or estimated) to derive spatially distributed latent heat flux maps (Cooper et al., 2000; Eichinger et al., 2000). It is the first time that the lidar has been used over such complex surfaces. Indeed, the study site was composed of three contrasting vegetation patches: the grassland which exclusively used surface water (rainfall), the mesquite which is able to extract water from deeper soil layers, and the cottonwood/willow forest gallery which transpires at or near a potential rate as its roots have ready access to ground water. Lidar-based estimates of latent heat flux compared well to values measured using eddy correlation over the grass and the mesquite patches and using sap flow for the cottonwood/willow riparian gallery. Kao et al. (2000) used an ultra-high resolution eddy simulation atmospheric model to understand the transport mechanisms

of humidity in the atmospheric surface and boundary layers under such complex conditions. Their model was able to simulate the general structure and evolution of the water vapor plumes observed by the lidar.

A large aperture scintillometer (LAS) has been used extensively to estimate area-averaged sensible heat flux, in the US during the 1997 Riparian campaign (Chehbouni et al., 1999) and in Mexico during 1997, 1998, and 1999 monsoon seasons. LAS-based values of area-averaged sensible heat flux were compared to observations over different surfaces with encouraging results (RMSE of about  $22 \text{ W m}^{-2}$ ). This leads us to conclude that the LAS is a reliable tool for the estimation of sensible heat flux at spatial scales compatible with those of meteorological models and remote-sensing satellites (Chehbouni et al., 2000b). However, the LAS requires estimates of area-averaged friction velocity values in order to derive sensible heat flux. The approach generally used consists of assuming that Monin–Obukhov similarity is conserved even above complex landscapes and also that an aggregation scheme for roughness is known. In this regard, Lagouarde et al. (2000) investigated the idea of using two scintillometers positioned at two different heights and sampling the same path to infer path average Monin–Obukhov length and thus the friction velocity. They reported that, even under homogeneous conditions, this method is very sensitive to measurement errors, particularly in near-neutral and very unstable conditions.

The use of these novel instruments (lidar and LAS) to validate aggregation schemes remains a theme for current research. However, progress has been made in representing the effects of heterogeneity of surface-controlling parameters in land-surface schemes. The approach used (the conceptual approach) consists of formulating grid-scale surface fluxes using the same equations that govern the patch-scale behavior but whose arguments are the aggregate expressions of those at the patch-scale. The strategy in linking local to aggregate or effective surface parameters can be either empirical (Shuttleworth, 1997; Avissar, 1992; Blyth and Harding, 1995; Sellers et al., 1997; Noilhan and Lacarrere, 1995; Noilhan et al., 1997) or theoretical (Raupach, 1991; McNaughton, 1994; Raupach and Finnigan, 1995; Lhomme et al., 1994; Chehbouni et al., 1995). The performance of three aggregation procedures, ranging

from physically based (theoretically derived) through semi-empirical to entirely empirical has been assessed by comparing measured and simulated area-average sensible heat flux. The results indicated that the physically based scheme performed very well. The performance of the entirely empirical scheme was reasonable but that of the semi-empirical scheme, which actually takes full advantage of remotely sensed data, was very poor. One possible explanation of the poor performance of this scheme might be due to the fact that non-linear relationships between model and observational variables are not universal or generic, but are scale dependent. Therefore, future research should be directed towards building robust relationships between model and observational variables directly at regional scale instead of trying to scale-up those developed at the local scale.

The theoretical approach is exact and elegant, but it requires knowledge of the patch-scale surface parameters involved in the parameterization of the exchange coefficients, and many of them cannot be derived from remote sensing. This is a major limitation for using such an approach in conjunction with a model that is operating at the grid scale in free running predictive mode (Shuttleworth et al., 1997). To overcome this difficulty, Shuttleworth (1998) outlined a practical strategy that combines, in an iterative way, multi-spectral remotely sensed data, a four-dimensional data assimilation model, and a semi-empirical aggregation scheme involving solely the variables that can be obtained via remote-sensing. This strategy needs to be implemented (using, for example, EOS data) and its performance evaluated.

### 2.3. *Vegetation functioning and competition of water between species*

It has been postulated that various large-area climatic factors, such as several severe droughts and a sequence of frequent ENSO events resulting in wet winters, have played a major role in accelerating shrub or mesquite invasion of the grassland. However, human activities, such as fire suppression and overgrazing, may have exacerbated this invasion (Swetnam and Bentancourt, 1998). One of the core components of the SALSA program is to understand the processes that lead to changes in vegetation type and structure in the basin (mesquite invasion and patch discontinu-

ity) and, more importantly, to document their impacts in terms of water resources and surface-atmosphere interactions.

In general, winter precipitation controls woody plant growth by recharging deep soil moisture, while summer rains drive the annual grass production that supports the livestock industry. This suggests that grasslands rely primarily on the summer precipitation, while mesquites access moisture from deeper soil. This behavior has been confirmed by the study carried out by Scott et al. (2000) in the floodplain area near Lewis Springs, AZ. They reported that the total evaporation from the grass was nearly equal to the summer precipitation, while that of the mesquite exceeded the precipitation by a factor of about 1.5. Similarly, in a study using sap flux and isotopic techniques during the rainy season, Snyder and Williams (2000) showed that the mesquite, at an ephemeral riparian site, derived a greater fraction of its transpiration water from the unsaturated soil zone. The investigation carried out over an extensive mesquite site in the top of an alluvial terrace in the Mexican side of the basin revealed somewhat different behavior. Over this site, the measured seasonal pattern of latent heat flux followed closely that of the surface soil moisture (5–10 cm), while deeper soil moisture (30–70 cm) remained almost unchanged throughout the rainy season. The soil contribution to the total latent heat flux was very small since the soil surface was characterized by a large rock fraction that produces rapid infiltration and runoff after the rainfall. Additionally, the atmospheric demand is very high, leading to a fast-drying of the soil surface layer. Therefore, one can conclude that the mesquite used mostly surface (rainfall) water, which implies that it is directly competing for water with the grass. In fact, isotopic analysis performed over the same site supports this conclusion, because the  $\delta^{18}$  value of the mesquite was close to that of rainfall. Apparently, the mesquite develops, along with its deeper roots, an extensive surface root system. This dual root system allows the mesquite to extract water from the shallow soil when this is available and to switch to deeper sources during the dry season. The conditions for this switch need to be documented and quantified and, more importantly, translated into the formulation for the canopy resistance to water transfer (Lhomme et al., 1998).



Grassland functioning has been heavily investigated during the SALSA program. Two vegetation growth models have been developed (or adapted) and validated using data collected over grassland sites in the San Pedro river basin (Nouvellon et al., 2000a; Cayrol et al., 2000a). The descriptions of the basic vegetation processes (carbon balance, photosynthesis, respiration, and senescence) in both models are not fundamentally different, but their parameterizations for energy and water exchanges are distinct, both in concept and complexity. The model developed by Nouvellon et al. (2000a) describes the flux of water and energy using a simple approach which functions with a daily time step, while that of Cayrol et al. describes these same processes using a detailed two-layer model over 20 min time steps. Both models have been validated using multi-year data sets (although for different sites), and they both show very good agreement between observed and simulated above-ground biomass, leaf area index, and the soil water content for different layers. The question that arises here is what is the level of complexity and at what time step the exchanges of water and energy need to be parameterized in a model for vegetation functioning in order to capture the seasonal and the interannual dynamics of the grassland. Apparently, a simple model with a daily time step might be sufficient. However, more analyses are required before a firm answer to this question can be provided. First, both models need to be run over the same site. Second, the advantage offered by the Cayrol et al. model, which allows the assimilation of instantaneous estimates of surface temperature and surface soil moisture using remote-sensing, needs to be weighed against the increase of the number of additional parameters required. Both of the above issues will be addressed within the SALSA program in the near future.

#### *2.4. Surface water ground water riparian vegetation interactions*

A critical and poorly understood component of the overall basin water balance is evapotranspiration of vegetation within the riparian corridor and the interactions between surface water and ground water which maintain the riparian system. Quantification of the total water loss to the atmosphere through transpiration and evaporation from this corridor is crucial to the

basin-wide water balance as well as to the ground water recharge/depletion process (Maddock et al., 1998). The problem, however, is that none of the classical micro-meteorological flux measuring devices (such as Bowen ratio or Eddy covariance) are appropriate for the narrow and relatively high cottonwood/willow forest gallery within the riparian corridor, because the required fetch conditions are not satisfied. This problem was addressed by integrating a variety of techniques from multiple disciplines including isotopic studies, tree sap flux measurements, micrometeorological measurements of sacaton grass and mesquite ET and simultaneous remote-sensing measurements, to enable scaling and to investigate the spatial and temporal variation of water utilization by the riparian corridor.

Using stable-isotope techniques, Snyder and Williams (2000) determined plant water sources in perennial, intermittent, and ephemeral stream reaches. They found that the willow's water source is almost entirely ground water; cottonwoods have some capability to utilize surface rains and runoff; and mesquite exhibits great flexibility in utilizing surface waters as they become available in the monsoon season. As noted above, Scott et al. (2000) concluded that the sacaton grasses at the Lewis Springs site were not acting phreatophytically-like, while the larger, more dense mesquites appeared to have access to deep vadose zone water or ground water. These studies and the study by Pool and Coes (1999) indicated a greater importance of rainfall and surface runoff processes supplying water to maintain the riparian system than was originally envisioned. Near-term climatic variability (seasonal to annual to interannual), in addition to ground water recharge and pumping, will therefore play a substantial role in the functioning of the riparian system.

By employing sap flux measurements at perennial and ephemeral sites, Schaeffer et al. (2000) concluded that the transpiration of cottonwood and willows per unit ground area declined with aging and successional development of the riparian gallery forest clusters. This has important implications for scaling tree- and cluster-level transpiration measurements using remotely sensed data because both the forest structural characteristics and successional cluster dynamics must be considered. Mac Nish et al. (2000) scaled the cottonwood/willow sap flux measurements from the tree to cluster to river reach stand level (~120 m) for

the two-day synoptic measurement periods in March, April, and June. Their study demonstrated basic agreement between the scaled sap flux ET estimates and those derived from a water balance. Goodrich et al. (2000b) built upon the studies and techniques discussed in the other SALSA papers referenced in this section to further scale the sap flux measurements, in space using remotely sensed data and in time using a calibrated Penman–Monteith model. This model was applied over a 10 km river reach during a 90-day pre-monsoon period. A water balance was calculated over this reach and period of time using the Penman–Monteith tree transpiration estimates and other independently derived water balance components. The overall closure of the water balance for this calculation was roughly 5%. This lends additional confidence to the methodology developed to estimate cottonwood/willow transpiration. When this model was applied over the entire corridor for the entire growing season, it was found that the total riparian ET from ground water was roughly 15% lower than the estimates based on a ground-water model (Corell et al., 1996). This result has significant implications for basin water management. However, additional investigations are needed to improve the accuracy of riparian ET, particularly during the monsoon season to obtain more accurate estimates of the amount of riparian ET derived from rain and surface runoff.

### *2.5. Assessment of land use and land cover changes in the basin*

The assessment of land use and land cover is an extremely important activity for contemporary land management. A large body of current literature suggests that human land-use management practices are the most important factor influencing ecosystem structure and functioning over a wide range of spatial and temporal scales. The type, magnitude, and distribution of land use are the major factors affecting contemporary ecological and hydrological conditions. The principal degradation processes that have occurred throughout the western rangelands involve (1) changes of vegetative cover, i.e., decrease in above-ground biomass and compositional diversity (primarily manifested by the introduction of exotic annual species or native woody xerophytic shrubs and trees) and (2) acceleration of water and wind erosion processes. Historically, these

have been linked to both human induced, and natural stressors, i.e., livestock grazing and short-term drought. However, rapid urbanization in the arid and semi-arid southwest, within the last 25 years has become an important factor in altering land-cover composition and pattern.

In the study performed by Kepner et al. (2000), a system of landscape pattern measurements derived from satellite remote-sensing, spatial statistics, process modeling, and geographic information systems technology has been implemented. These technologies provide the basis for developing landscape composition and pattern indicators as sensitive measures of large-scale environmental change and thus may provide an effective and economical method for evaluating watershed condition related to disturbance from human-induced and natural stresses. They utilized the database from the north American landscape characterization (NALC) project that incorporates triplicate Landsat multi-spectral scanner (MSS) imagery from the early 1970s, mid-1980s, and the 1990s. Landscape composition and pattern metrics were generated from digital land-cover maps derived from the NALC images and compared across a nearly 25-year period. The changes in land cover observed for the study period indicate that extensive, highly connected grassland and desert scrub areas are the ecosystems most vulnerable to encroachment of xerophytic mesquite woodland. In the study period, grasslands and desert scrub not only decreased in extent but also became more fragmented, that is, the number of grassland and desert scrub patches increased and their average patch sizes decreased. In stark contrast, the mesquite woodland patches increased in size, number, and connectivity (also see Table 3 and Fig. 4 of the preface paper to this special issue by Goodrich et al., 2000a). These changes have potentially important implications for the hydrology and ecology of the region as the energy, water, and nutrient balance characteristics for these land-cover types are often substantially different.

### **3. Concluding remarks**

The SALSA program has successfully employed a unique model of collaboration and utilization of shared resources to accomplish a substantial amount of research. It is certain that, during this first phase

of the program, we did not fully answer the entire scientific questions laid out during the SALSA workshop (Wallace, 1995). However, substantial progress has been made toward an improved understanding of the processes controlling the hydrological cycle, the ecological diversity, and the surface-atmosphere interactions in a semi-arid basin. Additional research questions have arisen and other unsolved issues have been identified.

The role of satellite measurements as a bridge between the length scales at which models operate and that of the field observations used for their validation has been demonstrated. The advantage of coupling different sensors for a better characterization of surface properties has also been emphasized. The need to take into account the directional effect on thermal infrared measurements has been identified as an important research task for the coming years. Future work should be directed toward developing, implementing and testing a near real-time model-driven data assimilation system which will have the capability of ingesting the earth observing system (EOS) and other remotely sensed observational data along with conventional data, with the objective of providing the best possible synthesized information for community use.

Research in land-atmosphere interactions undertaken during the SALSA program indicates that the selection of a SVAT for arid and semi-arid regions is not straightforward. There are many available options, which can generate very different results. It is not clear if a single scheme is appropriate for all the vegetation types and distributions encountered in these regions. Additionally, it is also important to consider the question of the objective to be achieved and therefore the time step at which the outputs of the model are needed (fraction of an hour, daily, seasonal) when selecting a surface scheme. Despite the fact that we successfully demonstrated the ability of novel instruments such as lidar/scintillometer to obtain spatially distributed/integrated convective surface fluxes over highly heterogeneous surfaces, the issue of surface heterogeneity is far from being solved. A tremendous amount of work is still required before the aggregation algorithms can be used operationally in free running (predictive mode) biosphere-atmosphere models.

In terms of ecology, different models for desert grassland functioning have been developed and suc-

cessfully validated. Light has also been shed on the functioning of the mesquite and its ability to effectively compete with grasses for surface water. However, research is needed to determine the periods and conditions in which vegetation phase (grassland-to-mesquite) transition commenced. More importantly, the development of models that can describe the physical and chemical processes leading to the mesquite invasion of the grassland is still lacking. These models should consider scenarios, such as climate variability, grazing, management, and fire.

The riparian research resulted in a major advance by providing an effective methodology to directly measure, model, and scale riparian tree transpiration derived from ground water in time and space. Valuable information on the dependence of riparian tree transpiration on structural and successional forest dynamics was acquired. Significant progress was made in identification of the water sources used by several riparian tree species, but further research is required to accurately assess the partition between ground water and surface waters during the monsoon season. Additional research is required to understand and quantify the spatial variability of precipitation as well as recharge processes (mountain front and ephemeral channel).

In a broader modeling context, it is also important to emphasize the future challenge of developing and implementing an integrated basin-scale hydrological, ecological, and atmospheric model to further integrate many of the initial research results presented herein. Indeed, the building of such an integrated model is crucial for addressing the SALSA Program's overall primary objective. For such a model to be an effective tool, not only for understanding the bio-physical processes of the basin, but as an aid to improve decision-making within the community, will require integration of physical science with social science. This is an additional critical challenge facing both SALSA researchers and the natural resource science community in general. This challenge must also be matched by the critical need to effectively communicate and apply SALSA results to policy makers and natural resource managers to help sustain the watershed for future generations. Publication of this special issue of SALSA results is a first step in meeting this challenge.

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